AGARD-R-752

AGARD-R-752

AD-A198 045

ADVISORY GR

AGARD REPORT No.752

Atmospheric Turbulence Research at DFVLR

NORTH ATL

DISTRIBUTION AND AVAILABILITY
ON BACK COVER

AGARD-R-752

NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Report No.752

ATMOSPHERIC TURBULENCE RESEARCH AT DFVLR

by

Anne M.Jochum
Institut für Physik der Atmosphäre
DFVLR
D-8031 Wessling
Federal Republic of Germany

Paper presented at the 64th Meeting of the Structures and Materials Panel in Madrid, Spain, 26 April–1 May 1987.

THE MISSION OF AGARD

According to its Charter, the mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

– Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community;

– Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);

– Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;

– Improving the co-operation among member nations in aerospace research and development;

– Exchange of scientific and technical information;

– Providing assistance to member nations for the purpose of increasing their scientific and technical potential;

– Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field.

The highest authority within AGARD is the National Delegates Board consisting of officially appointed senior representatives from each member nation. The mission of AGARD is carried out through the Panels which are composed of experts appointed by the National Delegates, the Consultant and Exchange Programme and the Aerospace Applications Studies Programme. The results of AGARD work are reported to the member nations and the NATO Authorities through the AGARD series of publications of which this is one.

Participation in AGARD activities is by invitation only and is normally limited to citizens of the NATO nations.

The content of this publication has been reproduced
directly from material supplied by AGARD or the author.

Published July 1988

ISBN 92-835-0462-3

Printed by Specialised Printing Services Limited
40 Chigwell Lane, Loughton, Essex IG10 3TZ

ABSTRACT

The paper gives a brief overview of work on atmospheric turbulence at DFVLR, and describes the research tools, which include instrumented aircraft and numerical models. Some results of research on turbulence characteristics are given; these are mostly in the convective boundary layer. The report discusses their application to the study of aircraft response and airframe loadings.

Paper presented to the Sub-Committee on Flight of Flexible Aircraft in Turbulence, under the chairmanship of Dr G.Coupry.

* * *

Ce rapport fournit une synthèse des travaux effectués au DFVLR sur la turbulence atmosphérique, avec une description des moyens de recherche employés, qui comprennent des aéronefs équipés d'instruments et des modèles numériques. Quelques résultats de recherche sur les caractéristiques de la turbulence y sont indiqués; ceux-ci concernent principalement la couche limite convective. Le rapport examine les possibilités des applications de ces résultats à l'étude de la réponse des aéronefs et de leurs structures aux contraintes de la turbulence. Le rapport a été présenté au sous-comité pour le vol des aéronefs à structure non-rigide en milieu turbulent, présidé par le Dr G.Coupry.

ATMOSPHERIC TURBULENCE RESEARCH AT DFVLR

Anne M. Jochum
Institut für Physik der Atmosphäre
DFVLR
D-8031 Weßling

SUMMARY

A brief overview of atmospheric turbulence work at DFVLR is presented. The main research tools covering aircraft and numerical models are described. Some results on turbulence characteristics mostly in the convective boundary layer are given, and their use for aircraft response and loads studies is illustrated.

1. INTRODUCTION

This report gives a brief overview on the status of atmospheric turbulence research mainly at the Institute of Atmospheric Physics of the German Aerospace Research Establishment (DFVLR) - with some limited reference to work going on elsewhere. The knowledge of atmospheric turbulence, in particular in lower altitudes, has advanced considerably due to both observational and modeling studies. From the available experimental and numerical data a variety of simple models (analytical formulae) have been derived. A recent and comprehensive review of the state of the art with particular reference to engineering applications is given by Panofsky and Dutton (1984).

The material presented may contribute to aircraft response and loads studies in two ways: firstly, to supply additional data sets from various altitude ranges and meteorological conditions, and secondly, to provide a basis consisting of a theoretical framework and a complete data base for testing different approaches (and possibly, to derive a unified procedure).

The paper consists of two main parts: one to introduce briefly the various research tools available for atmospheric turbulence studies at DFVLR, and another to describe several results that are believed to be of importance to aircraft response and loads studies.

2. RESEARCH TOOLS

The complex nature of atmospheric turbulence (see Figure 1) makes it necessary to use a variety of research tools in a complementary and synergistic approach. The Institute of Atmospheric Physics uses several research aircraft and some numerical models. Figure 2 shows the different kinds of results that can be obtained from these tools.

2.1 Atmospheric research aircraft

The Institute of Atmospheric Physics is currently using eight research aircraft for various meteorological programs. Among these a two engine jet aircraft Dassault Falcon E and three instrumented ASK 16 powered gliders are fully (Falcon) or partly (motor gliders) equipped for the measurement of atmospheric turbulence and wind.

Falcon

The two-engine jet is a high altitude fast research aircraft instrumented for wind, turbulence and cloud physics measurements and able to carry remote sensing equipment. A description of the aircraft and some results of measurements are given by Fimpel (1987). A detailed manual was compiled by Meischner (1985). Figure 3 shows a side view with the locations of the sensors. Table 1 gives some aircraft parameters. The following modifications have been made to the basic aircraft:

- a noseboom of 1.8 m length for the installation of sensors in the least disturbed flow area,
- an attachment point for external loads on the bottom of the fuselage, which can be used for travel pods but is now mainly used for PMS droplet spectrometers,
- two photographic windows equipped with optical glass, 520 mm in diameter (alternatively, pressure proof pods allow operation of sensors without windows),
- four ports, 80 mm in diameter, in the top of the fuselage, which are used as inlets for air chemistry instruments and pyrradiometers,
- a sealable aperture 250 mm x 570 mm on the left hand side of the fuselage (special windows for optical and microwave remote sensors).

Part of the instrumentation for meteorological measurements is installed permanently, another part is optional depending on the purpose of the specific mission. Table 2 gives an overview of the instrumentation. Resolution and absolute accuracy of the main parameters are given in Table 3.

The data are recorded by a fixed-wired PCM unit. 160 channels are sampled with 10 Hz, 16 channels (for turbulence measurements) are sampled with 100 Hz each with a resolution of 12 bit. Measurement speed for turbulence studies is around 100 m/s. This gives a spatial resolution along the flight track of 1 m for turbulence variables and of 10 m for others.

Motor gliders

Due to their limited altitude range and payload the motor gliders are primarily used in the atmospheric boundary layer. A low flight speed enabling the resolution of very small scales on one hand and a high degree of flexibility on the other hand makes them the ideal research platform even for complex terrain studies. The investigation of the atmospheric boundary layer requires high spacetime resolution, and this is achieved by the utilization of three identically equipped aircraft.

The ASK 16 is a low-wing aircraft manufactured of wood and metal. Figure 4 illustrates the form and dimensions of the aircraft. The aircraft has two seats, the second seat may also serve to install additional equipment. Some aircraft parameters are given in Table 1.

All three aircraft possess identical instrumentation. A complete description of the measurement system and of data available from several field experiments is given by Jochum et al. (1984), a short survey by Jochum et al. (1987). Table 4 provides a list of equipment. The sensors for temperature, humidity and pressure are installed in and on the wing instrument pod. A pitot static tube protrudes forward from the point of the pod so that the total (static) pressure aperture(s) are 1440 (1311) mm forward of the wing leading edge. The two accelerometers are installed in close vicinity of the center of gravity. The two gyros are mounted in the cockpit panel and are equipped with pick-offs for data registration.

The speed range is between 75 km/h and 170 km/h. Measurement flights are conducted at approximately 120 km/h. There, the linear approximation of the aircraft lift equation used in the vertical wind calculation is valid.

The determination of vertical windspeed is based on the aerodynamic method described by Lenschow (1976). The parameters needed in the aerodynamic lift equation for the powered gliders ASK 16 are given by Hacker (1982). The method was extensively tested by flying special patterns (pilot-induced pitch and roll oscillations) in calm air with negligible vertical motion. The results (Hacker, 1982) show that the manoeuvre-induced perturbations are sufficiently damped by the method. Table 5 shows an overview over accuracies, resolution and scales attained under standard measurement flight conditions (120 km/h speed, 20-30 km flight legs).

A small digitalization system (MINIDIG) was developed at the Institute of Atmospheric Physics. There are 16 channels available with a resolution of 12 bits each. The sampling rate can be selected at .1, 1, 10 or 100 Hz. In general, data are recorded at 10 Hz (which is consistent with sensor response times). Thus, a spatial resolution along the flight path of 3-4 m is obtained.

Data

In general, the time series of basic physical variables are low-pass filtered with a cut-off frequency of 2 Hz (motor gliders) or 0.6 Hz (Falcon) (about 17 m) in order to eliminate high-frequency noise.

The data from the different aircraft are combined to yield vertical profiles of mean values, variances and spectral characteristics.

Various methods have been employed to assess and maintain a high overall quality of data. For details see the reports cited above. Willeke (1985) has analyzed intercomparison flights of ASK 16 and Falcon and finds good agreement.

2.2 Numerical models

Numerical models of different complexity have been developed at the Institute of Atmospheric Physics in order to simulate turbulence in the atmospheric boundary layer. A one-dimensional (1D) model with third-order closure (Finger and Schmidt, 1986) is able to predict the statistical behavior of a homogeneous convective boundary layer. It has prognostic equations for mean quantities and for variances and covariances (second moments). A three-dimensional (3D) model computes directly the motion of the large eddies and uses various parameterizations of the sub-grid scale turbulence (Schumann et al., 1987). Both models have been successfully compared to laboratory measurements (in a watertank) and to aircraft observations (Jochum and Schmidt, 1987).

The development of a 3D direct simulation model (resolving even the small turbulence scales) for stable homogeneous shear flows (Gerz, 1987) serves mainly basic research purposes.

3. RESULTS

There are various ways to describe turbulence. The two principally different approaches are illustrated in Figure 2:

- one realization of the complete three-dimensional flow field
- statistical methods (involving some kind of averaging) are used to obtain information about the most probable behavior:
  - spectral analysis allows determination of characteristic energy containing wavelengths, of turbulence intensity, and of dissipation rates,
  - probability distributions give additional information about skewness (third moment indicating the relation between vigorous updrafts and weak downdrafts) and kurtosis (forth moment characterizing the difference between peak gusts and mean variance).

Examples of results obtained from these different approaches are given consecutively. They all refer to the convective boundary layer. There the dominant contribution to turbulence energy comes from the vertical velocity component, which therefore has been chosen for presentation. The height of the convective boundary layer is defined as the level of the lowest temperature inversion and is denoted by z_i.

Three-dimensional flow field

A three-dimensional numerical model (Schumann et al., 1987) has been used to simulate the details of turbulent convection. The numerical grid size is reduced to the scale of turbulent eddies in the inertial subrange. The bigger portion of the turbulent kinetic energy is resolved, whereas the subgrid scale turbulence is modelled by second order closure. This technique is termed large eddy simulation (LES). In order to validate the method, model results have been compared to data obtained from a laboratory experiment. Figure 5-a shows a vertical x-z cross section of vertical velocity. The convective boundary layer is characterized by the domain with some strong updrafts and weaker downdrafts, whereas the velocities are generally small in the stable layer aloft. Figure 5-b shows a corresponding horizontal x-y cross section through the middle of the boundary layer, which confirms the picture of a few strong updrafts and many weak downdrafts.

Spectra

From the LES results vertical velocity spectra have been computed at various heights. Figure 6 shows an example for $z/z_i = 0.5$. There the inertial subrange exhibits the characteristic -5/3 slope (von Karman spectrum). The computed energy containing wavelength at about $\lambda_m = 1.3\, z_i$ is in good agreement with the observations.

Some authors have derived simple models (mostly analytic expressions) for spectra obtained from extensive field experiments. Kaimal et al. (1976) for example give universal curves for velocity spectra in terms of normalized coordinates. Figure 7 shows that vertical velocity spectra for different normalized height ranges z/z_i collapse into a single curve at the high frequency end, whereas the normalized peak wavelength λ_m^{-1} (low frequencies) depends on normalized height. This height dependence is further illustrated in Figure 8, where the dashed line represents the relationship (Caughey and Palmer, 1979)

$$\frac{\lambda_m}{z_i} = 1.8(1 - \exp(\frac{-4z}{z_i} - .0003\exp(\frac{8z}{z_i}))). \tag{1}$$

A further analytic expression for vertical velocity spectra in the lower half of the convective and neutral boundary layer is given by Hojstrup (1982). Figure 9 shows the formula and the agreement with measured data.

Probability distributions

An example of measured vertical velocity probability distributions at different height levels is given in Figure 10 (Jochum, 1985). There it is evident that the principal characteristics (variance, skewness, kurtosis) are height dependent and in general non-Gaussian. The complete flow fields shown partly in Figure 5-a and Figure 5-b also clearly indicate the non-Gaussian nature of the vertical velocity distribution for convective turbulence. The third moment $\overline{w'^3}$ (which is a measure of skewness) as shown in Figure 11 as a function of normalized height attains a maximum value of about .25 w_*^3 around the middle of the boundary layer (where the peak wavelength has a maximum, too).

Vertical velocity variance as a function of height is shown in Figure 12 (computed from two different numerical models) and Figure 13 (from observations). The analytical expression derived from the observations (Wilczak and Phillips, 1986)

$$\frac{\sigma_w}{w_*} = \left\{2.5(\frac{z}{z_i})^{2/3}[1 - .91\frac{z}{z_i}]\right\}^{1/2} \tag{2}$$

is given by the solid line in Figure 13. The convective scaling velocity w_* can be estimated from routine meteorological data (van Ulden and Holtslag, 1985).
Figure 19 shows the good agreement between vertical velocity variance profiles obtained from 3D LES simulations and motorglider measurements.

4. APPLICATIONS TO AIRCRAFT RESPONSE

During all measurement flights vertical and horizontal accelerations of the aircraft have been recorded as well. Even without knowing the aircraft's response characteristics (from a system identification) or the pilot induced movements (which are not yet measured), some conclusions about the dynamic reaction of the aircraft in turbulent air can be drawn. Spectral analysis shows clearly that the dominant turbulence wavelength has virtually no influence on the dominant response frequency which is around 0.3-0.6 Hz at all heights (Figure 16) and with dominance of shear or buoyancy production (Reinhardt, 1985). Inspection of probability distributions for the same datasets reveals marked differences with changing height (Figure 17) or turbulence production mechanism (Figure 15) for vertical wind velocity but virtually no differences for vertical aircraft acceleration.

The results of a different method of analysis are shown in Figure 18. There the contributions to the total variance resulting from different scale (or frequency) ranges are computed by appropriately filtering the time series (Jochum et al., 1987). Small scales represent turbulence of stochastic character, intermediate scale sizes are organized structures up to the boundary layer depth scale, and large scales refer tp eddy sizes larger than the boundary layer depth. Vertical velocity variance is produced mainly by intermediate size scales, whereas vertical aircraft acceleration variance is produced essentially by small scales.

5. CONCLUSIONS AND OUTLOOK

A brief overview of atmospheric turbulence work at DFVLR has been presented. This work concentrates on low altitude turbulence in the atmospheric boundary layer. There, the turbulence characteristics over homogeneous terrain are fairly well understood, and can be described in terms of a few parameters which can be estimated from routine meteorological data. The accuracy of this descripition is satisfactory for many application purposes.

Further research at DFVLR is aiming at understanding the atmospheric boundary layer over complex terrain and in changing meteorological conditions. Model development is continuing and will finally lead to a 3D LES model with orography and clouds. The three motor gliders are presently completed by an air motion sensing and high-accuracy satellite positioning system. The Falcon jet will have a new avionics and inertial reference system soon which is supposed to improve wind and turbulence measurements.

Both aircraft are presently being equipped with sensors measuring the pilot-induced movements, and a system identification is being performed. Then the complete dynamic response of the research aircraft in turbulent air can be measured. Analoguosly, models of the dynamic response are going to be added to the existing numerical models, so that the aircraft response can be computed, and results of computations can be compared to measured data.

6. REFERENCES

Caughey, S.J., and Palmer, S.G., 1979: Some aspects of turbulence structure through the depth of the convective boundary layer. Quart. J. Roy. Meteor. Soc., 105, 811-827.

Fimpel, H.P., 1987: The DFVLR meteorological research aircraft Falcon-E: Instrumentation and examples of measured data. Preprints Sixth Sympos. Meteor. Observ. Instr., New Orleans, Amer. Meteor. Soc.

Finger, J.E. und H. Schmidt, 1986: On the efficiency of higher order turbulence models simulating the convective boundary layer. Beitr. Phys. Atm. 59, 505-517.

Gerz, T., 1987: Direkte Simulation stabil geschichteter, homogen turbulenter Scherströmungen. Ph.D. Dissertation, Universität München.

Gerz, T. und Schumann, U., 1987: The pressure-strain correlation in a turbulent homogeneous shear flow under strongly stable stratification. Proceedings in Physics (G. Comte-Bellot, ed.), Springer-V. Berlin/Heidelberg. (in press)

Hacker, J.M., 1982: First results of boundary layer research flights with three powered gliders during the field experiment PUKK. Beitr. Phys. Atmos. 55, 383-402.

Hacker, J.M., 1985: Die Aufbereitung und einfache meteorologische Auswertung der Meßflüge der DFVLR Motorsegler mit Hilfe des Softwarepaketes RAMF. DFVLR-FB-85-57, 65 pp.

Hojstrup, J., 1981: A simple model for the adjustment of velocity spectra in unstable conditions downstream of an abrupt change in roughness and heat flux. Boundary Layer Meteorol., 21, 341-356.

Hojstrup, J., 1982: Velocity spectra in the unstable planetary boundary layer. J. Atmos. Sci., 39, 2239-2248.

Jochum, A.M., 1985: Measurements of the vertical structure of the convective boundary layer.
In: Hacker, J.M. und Jochum, A.M., Eds., (1985), Proceedings of the workshop MEMO '84 ("Meteorological Motorglider"), October 1-5, 1984, Oberpfaffenhofen. ESA TT-936, 91-97.

Jochum, A.M., and H. Willeke, 1986: An experimental study of turbulence structure of the convective boundary layer over complex terrain. Terra Cognita, 6, 363.

Jochum, A.M., M.E. Reinhardt und H. Willeke, 1984: Die drei Motorsegler der DFVLR - ein meteorologisches Meßsystem zur Untersuchung der atmosphärischen Grenzschicht. DFVLR-Forschungsbericht FB 84-50, 150pp.
English translation: ESA TT-920.

Jochum, A.M., M.E. Reinhardt and H. Willeke, 1987: Three DFVLR powered gliders - a meteorological measurement system for the investigation of the atmospheric boundary layer. Proc. Sixth Sympos. Meteorological Observations and Instrumentation, New Orleans, 217-220.

Jochum, A.M. and Schmidt, 1987: Turbulent transport in the convective boundary layer. Proc. EURASAP Sympos. on Aircraft Measurements in Relation to Air Pollution, Garmisch, 7.-9. Sept. 1987.

Kaimal, J.C., et al., 1976: Turbulence structure in the convective boundary layer. J. Atmos. Sci., 33, 2152-2169.

Lenschow, D.H., 1976: Estimating updraft velocity from an airplane response. Mon. Wea. Rev., 104, 618-627.

Meischner, P., Ed., 1985: User's manual for the Falcon system. ESA-TT-936 119 pp.

Panofsky, H.A. and J.A. Dutton, 1984: Atmospheric Turbulence. Models and Methods for Engineering Applications. Wiley-Interscience, New York, 397 pp.

Reinhardt, M.E.: Case studies on flux measurements along a low-leve. flight leg south of Munich. :l.Ln: Hacker, J.M. und Jochum, A.M., Eds., (1985), Proceedings of the workshop MEMO '84 ("Meteorological Motorglider"), October 1-5, 1984, Oberpfaffenhofen. ESA TT-936, 69-79.

Schmidt, H., 1985: Numerische Simulation von Rayleigh-Benard-Konvektion unter dem Einfluß von Scherung. DFVLR, IB 553 1/85.

Schmidt, H., Finger, J.E., Schumann, U., 1986: Comparison of Large Eddy Simulations of a Convective Layer with One-Dimensional Models. Terra cognita 6/3.

Schumann, U., Elgobashi, S. und Gerz, T., 1986: Direct simulation of stably stratified turbulent homogeneous shear flows. Proc. EUROMECH 199, in: Notes on Numerical Fluid Mechanics, 15 (U. Schumann & R. Friedrich, eds.), Vieweg, Wiesbaden, 245-264.

Schumann, U., Hauf, T., Höller, H., Schmidt, H. und Volkert, H., 1987: A mesoscale model for the simulation of turbulence, clouds or flow over mountains: formulation and validation examples. submitted to Beitr. Phys. Atm.

van Ulden, A.P. and A.A.M. Holtslag, 1985: Estimation of atmospheric boundary layer püarameters for diffusion applications. J. Climate Appl. Meteor., 24, 1196-1207.

Willeke, H.: A comparison of 'Falcon' data with 'powered glider' data.
In: Hacker, J.M. und Jochum, A.M., Eds., (1985), Proceedings of the workshop MEMO '84 ("Meteorological Motorglider"), October 1-5, 1984, Oberpfaffenhofen. ESA TT-936, 69-79.

Wilczak, J.M., and Phillips, M.S., 1986: An indirect estimation of convective boundayr layer structure for use in pollution dispersion models. J. Climate Appl. Meteorol., 25, 1609-1624.

Wyngaard. J.C., 1986: Measurement physics. In: Probing the atmospheric boundary layer, D.H. Lenschow, Ed., Amer. Meteor. Soc., 5-18.

	ASK 16	Falcon
maximum take-off weight (MTOW)	765 kp	13 000 kp
permanently-installed equipment	70 kp	included below
allowance for crew and fuel	200 kp	5 090 kp
range	700 km	1220 - 1680 km
		(depends on altitude)
service ceiling	8500 ft msl	42 000 ft
maximum rate of climb	2 m/s at 100 km/h	10 m/s

Table 1. *Selected aircraft specifications*

permanently installed sensors are:

- Pressure and wind:
  - Flow angle sensor Rosemount 858 J with transducer Rosemount 1201 for absolute (static) pressure and Rosemount 1221 for differential (impact, angle of attack and sideslip) pressures.
  - Inertial navigation sytem Litton 72.
- Temperature:
  - Two probes Rosemount 102 (fast and slow).
- Humiditiy:
  - Dew point sensor General Eastern 1011.
  - Relative Humidity sensor Vaisälä Humicap.
  - Absolute Humiditiy sensor ERC Lyman α.

  The Humicap and the Lyman α sensors are mounted inside the fuselage in a tube. On its inlet the housing the Rosemount temperature sensor is fixed. Close to the humidity sensors the temperature and the pressure are measured in the tube. So the influences of the heating of the air and the rise of the pressure in the tube of the humidity measurements can be corrected.
- Liquid water content:
  - Cloud technology (Johnson-Williams) Sensor CT-10.

Optional sensors are:

- Radiation:
  - Pyranometer Eppley PSP (upward and downward).
  - Pyrgeometer Eppley PIR (upward and downward).
  - Radiometer Barnes PRT6 (downward).
- Cloud Physics:
  - Droplet spectrometer PMS FSSP-100.
  - Droplet spectrometer PMS OAP-230X.
  - Liquid water content sensor PMS CSIRO-King.
- Aaerosol Lidar:
  - Airborne Lidar System DFVLR ALEX-F1.

Table 2. Instrumentation Falcon (from Fimpel, 1987)

absolute accuracy of main parameters		
Parameter	Resolution	Accuracy
Static pressure	±0.12	±1.5 hPa
Impact pressure	±0.06	±1.2 hPa
Temperature	±0.02	±0.5 K
Relative humidity	±0.02	±2.0 %
Absolute humidity	±0.01	±0.7 g/m³
Horizontal wind components	*)	±5.0 m/s
Vertical wind component	*)	±0.8 m/s
*) Computed from several parameters		
horizontal resolution	1 m	
scales	5.5 m - 5 km	
altitude range	30 m agl - 12 km msl	

Table 3. Standard data characteristics Falcon (from Meischner, 1985)

Temperatures

- reverse flow temperature probe (Pt 100 manufactured in-house)
- Pt 100 in humidity channel (manufactured in-house)
- Barnes PRT-5 radiation thermometer (one aircraft only)

Humidity

- ERC Lyman-alpha hygrometer
- Vaisälä humicap relative humidity sensor

Pressure

- Rosemount static and dynamic transducers for pitot static tube

Aircraft motion

- Sundstrand accelerometer (2)
- SFENA vertical gyro (pitch and roll angle)
- AIM directional gyro (heading)

Video camera(s) looking forward and/or downward (optional)

Table 4. Instrumentation ASK 16 (from Jochum et al.,1987)

relative accuracy of derived quantities	
potential temperature	± .07 K
specific humidity	± .05 g/kg
vertical wind speed *)	± 2 m/s
height	± 20 m (abs.)
*) includes only errors of input parameters	
horizontal resolution	3.3 m
scales	16.5 m - 3.3 km
altitude range	30 m agl - 2.5 km msl

Table 5. Standard data characteristics ASK 16 (from Jochum et al., 1987)

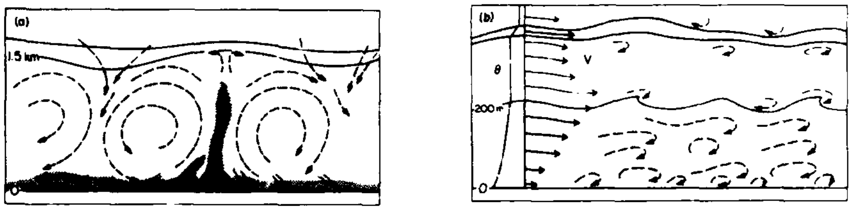


Figure 1. **Turbulence structure of the atmospheric boundary layer:** schematic view (from Wyngaard, 1986) of (a) the convective boundary layer capped by an inversion and (b) the stably stratified nocturnal boundary layer.

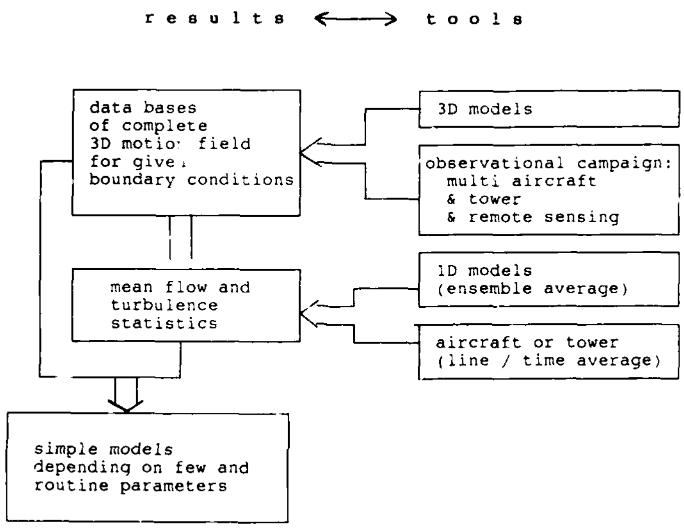
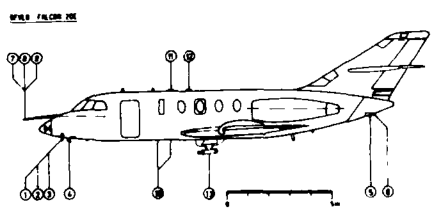


Figure 2. **Tools in atmospheric turbulence research.**



1: Temperatur
2: Humidity
3: Johnson-Williams LWC
4: Outlet of the 'humidity tube'
5: Pyrgeometer downward
6: Pyranometer downward
7: Static pressure
8: Impact pressure
9: Flow angle sensor
10: Photo windows (Lidar system)
11: Pyranometer upward
12: Pyrgeometer upward
13: Droplet spectrometer and CSIRO-King LWC

Figure 3. **Falcon with instrumentation** (from Fimpel, 1987).

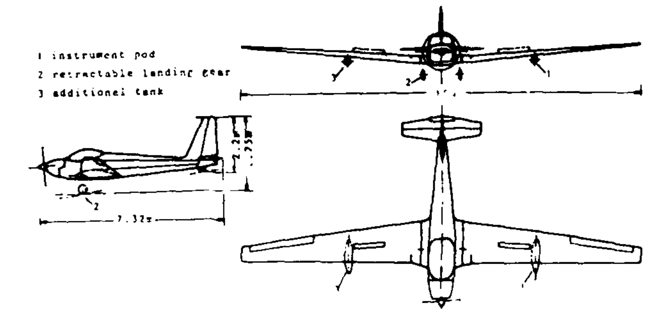


Figure 4. ASK 16 with instrumentation (from Jochum et al., 1987).

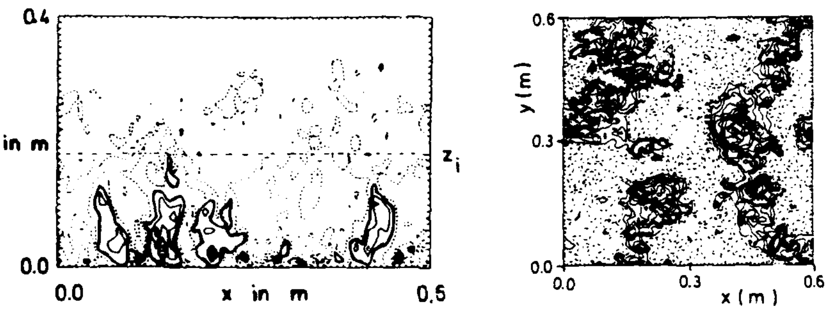


Figure 5. ***Vertical velocity component w:*** (a) in an x-z cross section (from Schumann et al., 1987); isoline increment $0.5w$; solid (dashed) lines represent positive (negative) values. (b) x-y cross section at $0.62z_i$; solid (dashed) lines denote updrafts (downdrafts); isoline increment .002m/s. (Schmidt, 1987, personal communication).

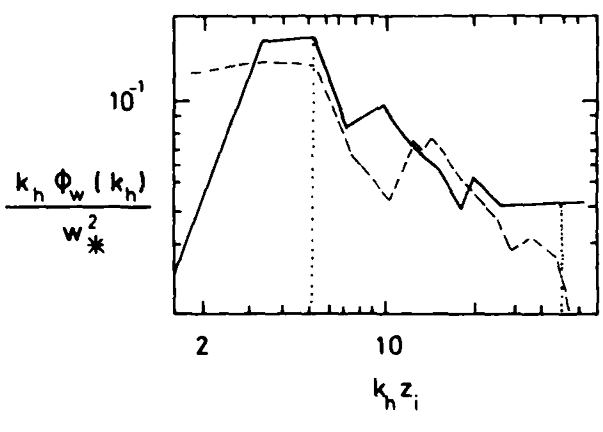


Figure 6. Vertical velocity spectrum from LES simulation at $0.6z_i$ (from Schumann et al., 1987); solid (dashed) lines denote computed (measured in a watertank) values.

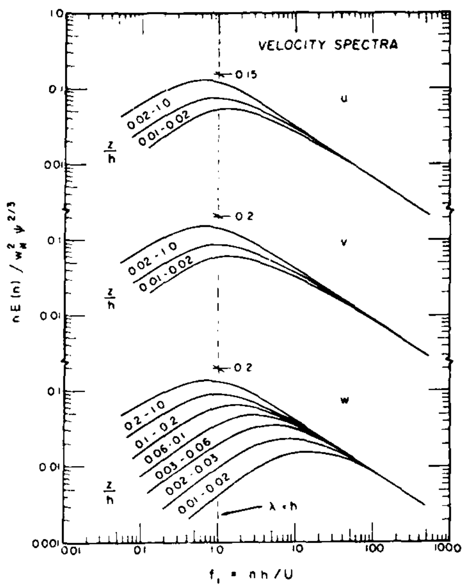


Figure 7. **Normalized velocity spectra from observations** expressed in mixed-layer similarity coordinates (Kaimal et al., 1976).

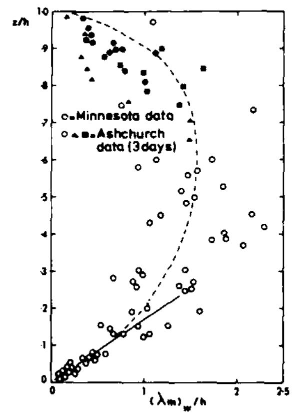


Figure 8. **Normalized peak wavelength from observations** (from Caughey and Palmer, 1979). The dashed line represents the relationship (1), h denotes the inversion height.

$$\frac{nS_w(n)}{u_*^2} = F\left(f, \frac{z}{z_i}\right) \frac{0.95\, f_i}{(1 + 2 f_i)^{5/3}} \left(\frac{z_i}{-L}\right)^{2/3} + \frac{2f}{1 + 5.3\, f^{5/3}} \left(1 - \frac{z}{z_i}\right)$$

$$F\left(f, \frac{z}{z_i}\right) = \left(\frac{f^2 + (0.3\frac{z}{z_i})^2}{f^2 + 0.0225}\right)^{1/2}$$

$$f_i = n\frac{z_i}{u} \qquad f = \frac{nz}{u}$$

best fit for $z = 0.1\, z_i$:

$$\frac{\sigma_w}{u_*} = \left(1.1 + 1.7\left(\frac{z}{-L}\right)^{2/3}\right)^{1/2}$$

Figure 9. **Vertical velocity spectra and variance: Hojstrup formula** (from Hojstrup, 1982). The surface layer friction velocity u_* and the Monin-Obuchow length L can be estimated from routine meteorological parameters (van Ulden and Holtslag, 1985)

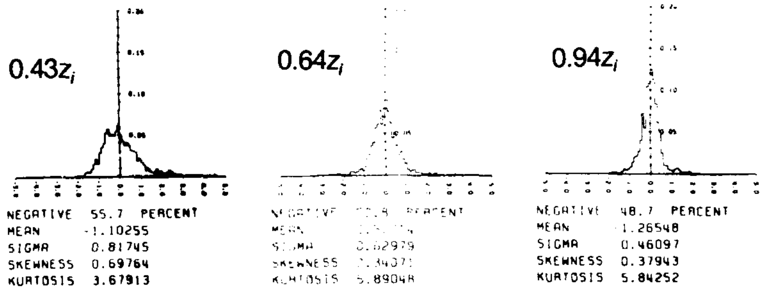


Figure 10. Vertical velocity probability distributions from observations at different heights. The abscissa is labelled vertical wind, m/s.

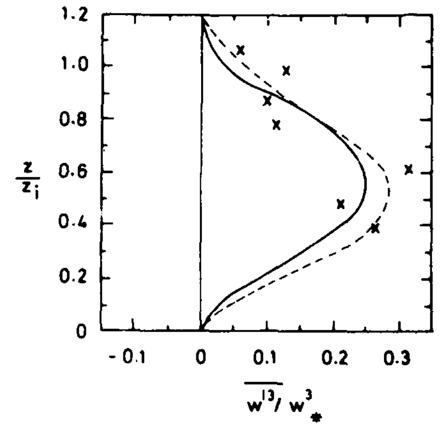


Figure 11. Vertical velocity skewness as a function of height (from Schumann et al., 1987). solid (dashed) lines denote computed (measured in a watertank) values.

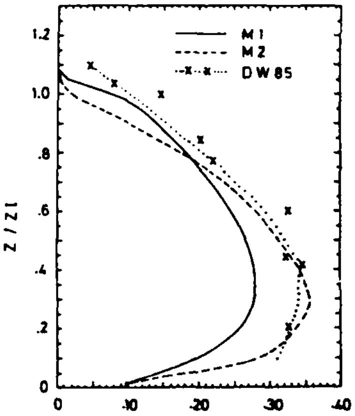


Figure 12. Vertical velocity variance from model simulations (from Finger and Schmidt, 1986), normalized with w_*. DW 85 denotes measurements in a watertank, M1 and M2 are models with different turbulence parameterization.

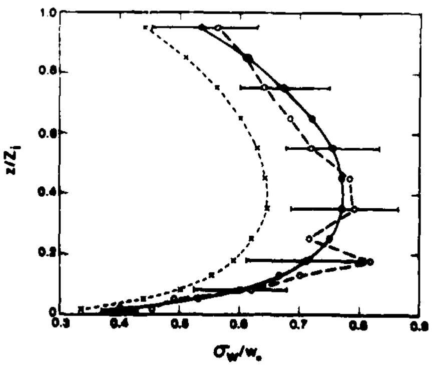


Figure 13. Vertical velocity variance from observations (from Wilczak and Phillips, 1986). The solid line is given by relationship (2), the heavy dashed line represents observations.

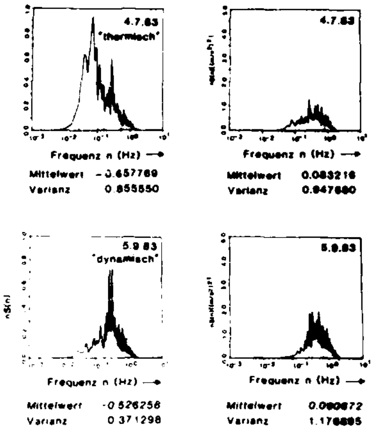


Figure 14. **Measured spectra of vertical wind (left)** and **vertical acceleration** of aircraft (right): shear produced (below) versus buoyancy produced (above) turbulence.

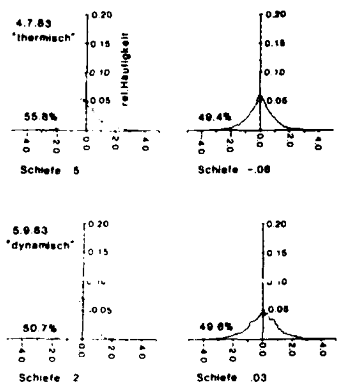


Figure 15. **Measured distributions of vertical wind (left) and vertical acceleration** of aircraft (right): shear produced (below) versus buoyancy produced (above) turbulence.

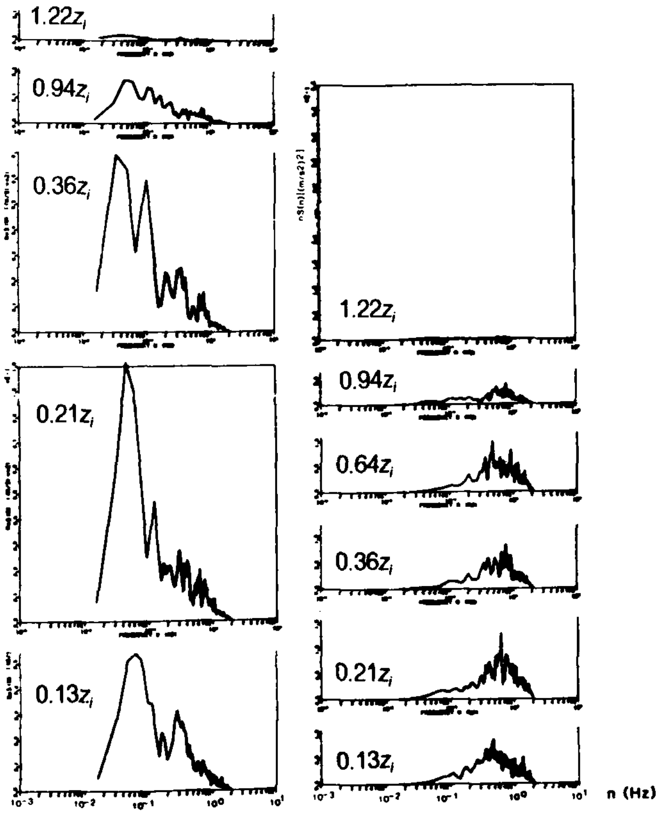


Figure 16. **Measured spectra of vertical wind (left)** and **vertical acceleration** of aircraft (right): height dependence.

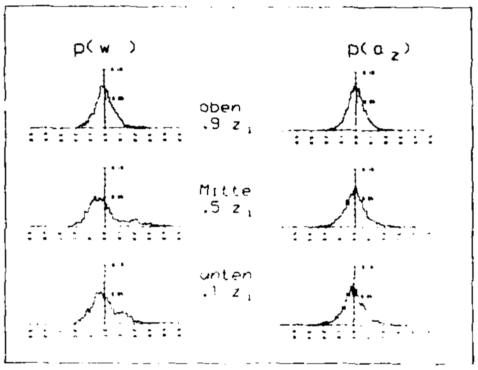


Figure 17. **Measured distributions of vertical wind (left) and vertical acceleration** of *aircraft (right): height dependence.*

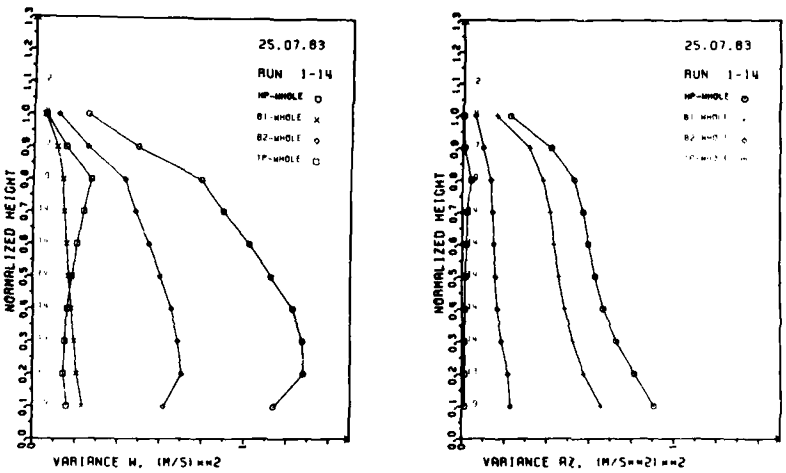


Figure 18. **Contributions of scale ranges to measured variances** of vertical wind and vertical aircraft acceleration. HP denotes total variance, B1 contribution of small scales, *B2 contribution of intermediate scales, TP of large scales.*

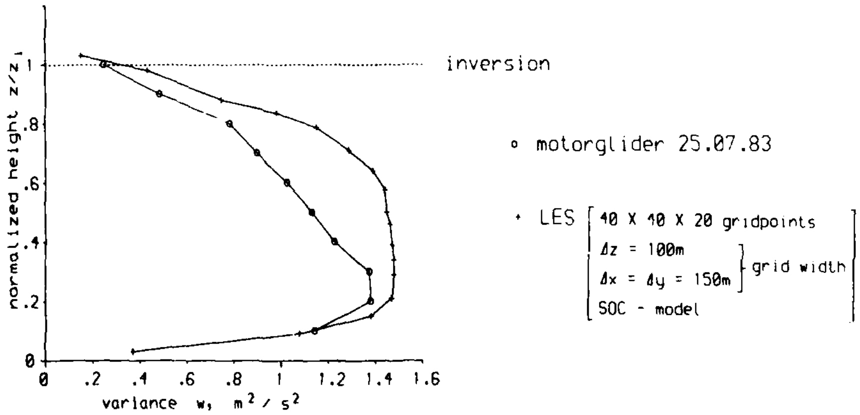


Figure 19. **Comparison of 3D LES simulation and aircraft observations:** vertical profiles of vertical wind variance.

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-R-752	ISBN 92-835-0462-3	UNCLASSIFIED

5. Originator	Advisory Group for Aerospace Research and Development North Atlantic Treaty Organization 7 rue Ancelle, 92200 Neuilly sur Seine, France
6. Title	ATMOSPHERIC TURBULENCE RESEARCH AT DFVLR
7. Presented at	the 64th Meeting of the Structures and Materials Panel in Madrid, Spain 26 April — 1 May 1987.

8. Author(s)/Editor(s)	9. Date
Anne M.Jochum	July 1988

10. Author's/Editor's Address	11. Pages
See flyleaf.	18

12. Distribution Statement	This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications.

13. Keywords/Descriptors

Turbulence	Mathematical models
Test facilities	Aircraft
Boundary layer	

14. Abstract

The paper gives a brief overview of work on atmospheric turbulence at DFVLR, and describes the research tools, which include instrumented aircraft and numerical models. Some results of research on turbulence characteristics are given; these are mostly in the convective boundary layer. The report discusses their application to the study of aircraft response and airframe loadings.

AGARD Report No.752	AGARD-R-752
Advisory Group for Aerospace Research and Development, NATO ATMOSPHERIC TURBULENCE RESEARCH AT DFVLR by Anne M.Jochum Published July 1988 18 pages The paper gives a brief overview of work on atmospheric turbulence at DFVLR, and describes the research tools, which include instrumented aircraft and numerical models. Some results of research on turbulence characteristics are given; these are mostly in the convective boundary layer. The report discusses their application to the study of aircraft response and airframe loadings. P.T.O.	Turbulence Test facilities Boundary layer Mathematical models Aircraft

AGARD Report No.752	AGARD-R-752
Advisory Group for Aerospace Research and Development, NATO ATMOSPHERIC TURBULENCE RESEARCH AT DFVLR by Anne M.Jochum Published July 1988 18 pages The paper gives a brief overview of work on atmospheric turbulence at DFVLR, and describes the research tools, which include instrumented aircraft and numerical models. Some results of research on turbulence characteristics are given; these are mostly in the convective boundary layer. The report discusses their application to the study of aircraft response and airframe loadings. P.T.O.	Turbulence Test facilities Boundary layer Mathematical models Aircraft

AGARD Report No.752	AGARD-R-752
Advisory Group for Aerospace Research and Development, NATO ATMOSPHERIC TURBULENCE RESEARCH AT DFVLR by Anne M.Jochum Published July 1988 18 pages The paper gives a brief overview of work on atmospheric turbulence at DFVLR, and describes the research tools, which include instrumented aircraft and numerical models. Some results of research on turbulence characteristics are given; these are mostly in the convective boundary layer. The report discusses their application to the study of aircraft response and airframe loadings. P.T.O.	Turbulence Test facilities Boundary layer Mathematical models Aircraft

AGARD Report No.752	AGARD-R-752
Advisory Group for Aerospace Research and Development, NATO ATMOSPHERIC TURBULENCE RESEARCH AT DFVLR by Anne M.Jochum Published July 1988 18 pages The paper gives a brief overview of work on atmospheric turbulence at DFVLR, and describes the research tools, which include instrumented aircraft and numerical models. Some results of research on turbulence characteristics are given; these are mostly in the convective boundary layer. The report discusses their application to the study of aircraft response and airframe loadings. P.T.O.	Turbulence Test facilities Boundary layer Mathematical models Aircraft

Paper presented to the Sub-Committee on Flight of Flexible Aircraft in Turbulence, under the chairmanship of Dr G.Coupry.

ISBN 92-835-0462-3

Paper presented to the Sub-Committee on Flight of Flexible Aircraft in Turbulence, under the chairmanship of Dr G.Coupry.

ISBN 92-835-0462-3

Paper presented to the Sub-Committee on Flight of Flexible Aircraft in Turbulence, under the chairmanship of Dr G.Coupry.

ISBN 92-835-0462-3

Paper presented to the Sub-Committee on Flight of Flexible Aircraft in Turbulence, under the chairmanship of Dr G.Coupry.

ISBN 92-835-0462-3